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Working on the Moon : The Apollo Experience

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Introduction

The successful completion of any scientific or engineering project on the Moon will depend, in part, on human ability to do useful work under lunar conditions. In making informed decisions about such things as the use of humans rather than robots for specific tasks, the scheduling of valuable human time, and the design and selection of equipment and tools, good use can be made of the existing experience base.

During the six completed landing missions, Apollo lunar surface crews conducted 160 astronaut-hours of extra-vehicular activities (EVAs) and also spent a similar sum of waking hours working in the cramped confines of the Lunar Module. The first three missions were primarily proof-tests of flight hardware and procedures. The ability to land equipment and consumables was very modest but, despite stay times of no more than 32 hours, the crews of Apollos 11, 12, and 14 were able to test their mobility and their capability of doing useful work outside the spacecraft. For the last three missions, thanks to LM modifications which enabled landings with significant amounts of cargo, stay times more than doubled to three days. The crews were able to use Lunar Rovers to conduct extensive local exploration and to travel up to 10 kilometers away from their immediate landing sites. During these final missions, the astronauts spent enough time doing work of sufficient complexity that their experience should be of use in the formulation early-stage lunar base operating plans.

Apollo Constraints

Time constraints were the dominant fact of life in Apollo. Short stays were ultimately the result of political rather than of technical factors; and, particularly, to decisions that, (1) the Apollo hardware would be designed to land crews; and, (2), there would be only a finite number of flight opportunities.

As defined in 1961, the basic Apollo mission was to land astronauts on the Moon and return them safely to Earth before the end of the decade. Because of the deadline, NASA had no choice but to design the sparest possible set of flight hardware capable of satisfying the Kennedy criteria. (e.g. Cortright 1975) Even with the LM upgrades, other than the mass of the descent stage engines and structures, NASA could only land about 6.0 metric tons on the lunar surface. Because the vehicle had to carry a crew, little of that tonnage could be spared for stocks of consumables and non-flight related equipment.

Had there been an opportunity to build an unmanned, cargo version of the LM Descent Stage and to use it for repeated landings at a single site, NASA could have accumulated assets to support very long stays and, eventually, a lunar base. However, because NASA's first priority was a manned landing and because the cost of the core program was high enough to strain political support, development of a cargo lander could not have been contemplated until design and testing of the piloted vehicle was virtually complete. At mid-decade, as spending on the development of the Saturn V, the LM, and the CSM began to decline, there was some hope that funds could then be allocated to lunar base and Mars programs; but political support never emerged and, in 1970, NASA was even forced to cancel three flights for which hardware had already been built (e.g. McDougall 1985)

During Apollo, NASA was never in a position to contemplate an accumulation of lunar assets and was only able to conduct a broad survey of lunar geologic history by sending minimally-equipped crews to a half dozen widely-scattered sites. Because stay times were short, almost every available minute was carefully allocated. There was some flexibility in the EVA time-lines and some allowance was made for unexpected difficulties and/or discoveries; but the slack never amounted to more than a few minutes. When serious difficulties were experienced, completion of a task came only at the expense of dropping something else. For example, some equipment design flaws on Apollo 15 forced Scott and Irwin to spend an extra hour completing drilling tasks, an hour which then had to be deducted from the length of their final geology traverse. Indeed, it was a credit to the planners and the crews that, because of careful use of simulation and training and careful assessment of the work load, few serious problems were encountered.

At a lunar base, with stays of several months, with hundreds of tons equipment, supplies and structures, and with frequent opportunities to modify equipment, procedures, and schedules, there will be considerably greater operational flexibility. However, although time pressures will be less important at a lunar base than during Apollo, the number and types of tasks which can be undertaken and the rate with which they can be completed will depend on many of the same basic factors - mobility, communications, team work, vulnerability to dust abrasion, and the like - which were important during Apollo.

Astronaut Mobility and Metabolic Rates

An astronaut's speed, confidence, and efficiency while moving will determine such things as the optimum mix of walking and riding time during traverses and will set limits on excursions ranges in the interest of a safe return to base following a vehicle breakdown. With each successive Apollo mission, crews increased their range of operations, accumulated data on mobility and metabolic rates, and gained the confidence and efficiency that comes with experience.

Learning how to walk and run effectively required adaptation not only to lunar gravity but also to the stiffness of the inflated suit, the bulk of the boots, the dramatic upward shift in center-of-mass caused by the backpacks, and, the the astronauts' inability to see their feet and such hazards as rocks, soft crater rims, and foot-grabbing cables. Because of training exercises conducted in aircraft flying 1/6-g trajectories, basic proficiencies were acquired in a matter of a few minutes. On Apollo 11, Armstrong and Aldrin quickly confirmed that they could walk short distances, carry and deploy equipment, and gather samples. On the longer missions, crews had time enough that gaits and hazard avoidance techniques (such as backing up as seldom as possible) became semi-automatic. On Apollo 15, for example, even though Scott and Irwin never made a traverse of more than 200 meters, they increased their average walking speed from about 1 km/hr to about 1.5 km/nr during EVA 1, and then to 2.0 km/hr during EVA 2.

The first information relevant to the conduct of long traverses and emergency returns came on Apollo 12. During their second EVA, Conrad and Bean covered one 300 meter stretch up a shallow, three-percent grade at a speed of about 4 km/hr but then had to rest for a few minutes to get their heart rates and breathing under control. On Apollo 14, Shepard and Mitchell made the most difficult of the long Apollo traverses, climbing a ten-degree slope during the second half of their 1.4 km walk to the rim of Cone Crater. Although they tried to maintain a deliberate pace, they found they could only walk for a few minutes at a time before their breathing became labored and they had to stop to rest. Not including science stops, their average outbound speed was only about 1.7 km/hr. Not surprisingly, on the trip back to the LM the walking got to be fun again and, going downhill, Shepard and Mitchell doubled their average speed.

Using this experience, NASA estimated that, with some care taken in avoiding long uphill slopes, crews making emergency return to the LM could average 3.6 km/hr for periods of up to an hour, and 2.5 km/hr for longer periods. A return from a distance of 10 kilometers could, then, be completed in about 4 hours, provided only that the astronauts had sufficient consumables left. The rates of oxygen and cooling water consumption were related to equivalent metabolic rates. Oxygen use was about 0.16 lb/hr per 1000 BTU/hr; and, in addition to about 0.3 lbs/hr for equipment cooling, cooling water use was about 1.2 lbs/hr per 1000 BTU/hr. Typical metabolic rates were 1000 BTU/hr while working around the LM or a Rover, 550 BTU/hr while riding, 1290 BTU/hr while walking at 2.7 km/hr, and 1560 BTU/hr at 3.5 km/hr.

Working in stiff suits

Other than time constraints, getting work done during the Apollo EVAs was controlled primarily by the stiffness of the inflated suits. The suits would bend reasonably well at the knees and waist but, because of both the stiffness and the high center-of-mass, getting low required a means of support if an astronaut wanted to stand again. Neither Armstrong nor Aldrin tried to bend over enough to pick objects with their hands nor tried to kneel. As planned, they used tongs and scoops to grab samples and dropped equipment. Conrad and Bean discovered such tricks as using their tools and their tool rack as supports and using the straps attached to the backpacks as a kind of toddler's harness. By the last few missions, astronauts were occasionally seen kneeling next to equipment or reaching down to pick up rocks, although getting back up usually involved a frantic running-in-place as the astronaut tried to get his feet under his high center of mass. The astronauts had a number of long handled tools; but there were always cases when the right tool wasn't close at hand, an interesting sample was too big to grab with a tool, or a bolt was in an awkward position. At such times, the extraordinary effort necessary to get within arms-length of the ground sometimes seemed worthwhile.

The stiffness of the suit arms was particularly irksome when an astronaut tried to work alone. For example, during solo attempts to sample soil, the astronaut would have to hold the end of the loaded scoop in one hand, an open sample bag in the other, and then, with both arms extended, try to pour the soil into the bag. For two people, soil sampling was easier: one person manipulating the scoop, the other the bag. Indeed, many tasks could be done most efficiently if the astronauts worked as a team, each with a practised set of actions to perform.

Suit stiffness also produced severe forearm fatigue. Any movement or positioning of a leg, arm, hand, or finger away from the "rest" configuration of the pressurized suit required constant muscle tension and, because of nearly constant use, the forearm muscles suffered most. As Jack Schmitt has described the problem, "it was like squeezing a tennis ball repetitively. Within a half hour or so, the forearm muscles were sufficiently fatigued to ache and you reached a much lower level of productivity using your hands than when you started. Eventually, by pacing yourself, you reached a constant level of forearm pain such that you could tolerate it and still do the job and not drop things and still apply sufficient grip to work; and that then went on for the rest of the EVA. Fortunately, after a night's rest and sleep, that soreness went away. There was no residual soreness; and I think that's related to the lower gravity environment. On the Moon, your heart and cardiovascular system are so much more efficient in removing the products of metabolism such as lactic acid that you never damage any muscle fiber. You fatigue it, but you don't damage it. And the important thing was that, with rest, the soreness went away. It came back when you went out again and started work, but it wasn't compounded."

And finally, there was physical trauma that resulted from repeated reaching within the gloves. According to Schmitt "as you reached in the suit and just got a little bit of scraping from the rubber bladder, it grabbed at your fingernail and, eventually, lifted the nail right off the quick. It was a problem we knew about before the mission, because everyone else had experienced it. Knowing that, I wore some nylon liners. I still had the problem, but not as rapidly as Gene Cernan, who didn't wear any liners. Ultimately, all my nails were lifted off the quick. And that was just continuous, traumatic soreness which faded into the background and you didn't worry about it. I don't recall having rough or damaged fingertips, but I think Gene and a lot of the other guys did."

Clearly, on missions of no more than a few days' duration, the consequences of stiff suits were tolerable. But, for longer stays, attention needs to be paid both to suit flexibility and to reduction of internal scraping and pulling. Indeed, careful attention to equipment design and testing will be critical to long-term efficiency and productivity.

Inadequate equipment testing/faulty designs

Under any novel circumstances or conditions of first use, some equipment is not going to work as expected. Indeed, it would have been surprising had there been no equipment problems experienced during the landings. Because time was at such a premium, failures had the potential for serious losses of productivity and there were at least a few cases when a bit more attention to the design of particular pieces of lunar surface equipment could have produced a substantial return.

Understandably, NASA devoted most of its Apollo effort to the design and testing of equipment essential to the achievement of landings and the safe return of crews. Flight hardware came first; suits and life support systems came second; and then everything else. Even for such prominent items as the Apollo Lunar Surface Experiment Package (ALSEP) and the Lunar Rover, development and production contracts were not let until 1966 and 1969 respectively; and, although representatives of the astronaut corps were sometimes involved in design activities right from the beginning (as with the Rover), some equipment became available for testing and familiarization only late in a mission training cycle. Crews had to be insistent to keep unfamiliar equipment off a flight manifest. As Pete Conrad implied during his mission, it was pleasure to open the LM equipment bay and find only "things I've seen before." Familiarity reduced the chance for surprises and the waste of extremely valuable time.

Some equipment problems were due to fundamental design flaws. On Apollo 11, short core tubes which Aldrin was supposed to push and then hammer into the ground, had been mistakenly designed with an internal bevel which compacted soil entering the tube. If the soil was fairly loose, the compaction wasn't severe enough to clog the core tube; but, on the Moon, natural soil compaction tends to increase dramatically with depth and, after pushing the two tubes in about 3 to 5 inches, Aldrin was able to hammer them only about 2 inches deeper. On Apollo 12, one of the experiment modules, its weight so much lower on the Moon than on Earth, wouldn't sit upright but, rather, was flipped on its side by residual spring in the cables connecting it with the ALSEP central station. On an Apollo 15 heat flow experiment, drill stems had been been designed primarily with thermal characteristics in mind failed wouldn't penetrate the compact soils encountered at depth. And, finally, on Apollo 17, a gravity wave detector which Schmitt has described as "the only Nobel-class experiment yet taken to the Moon" - failed because of the manufacture's insistence that one-sixth g, pre-launch tests would reveal proprietary information and, therefore. should not be performed. As it turned out, such tests would have revealed a small error in the design of a balance beam at the heart of the device, an error large enough to prevent the beam from uncaging under lunar gravity conditions. These problems and others caused a considerable lose of data, both directly and through the collective, unplanned consumption of well over an hour of EVA time.

Other problems can be better ascribed to insufficient testing and training, most prominently in the case of the Apollo 15 deep core hole. Here, design of the drill stem was excellent but Scott and others had been working as late as the week before launch to devise procedures so that he could manually extract the core from compact soils. The effort was unsuccessful and Scott and Irwin extracted the core - sometimes described as as one of the most important samples yet returned from the Moon - only at a cost of about 15 extra minutes of EVA time and a severe (but unremarked) shoulder sprain suffered by Scott. (Later crews had a treadle and jack which made the job a great deal easier.) And then, to add insult to the literal injury, Scott also discovered that the vise mounted on the back of the Rover would not grip the core sections when he tried to separate them for transport back to Earth. As it turned out, engineering drawings used for Rover assembly showed the vise mounted backwards from its proper orientation. However, during assembly of the training unit, the vise had been installed backwards from the drawing and, consequently, the error wasn't discovered until Scott and Irwin were on the Moon.

Repair: Gray Tape

In a lunar base era, an accumulation of experience with lunar conditions will aid in equipment design and testing and, with proper attention, should reduce the relative frequency with which inappropriately designed and/or inadequately tested equipment is delivered. However, because local fabrication capabilities will emerge only slowly, there will be a on-going need to modify and repair gear brought to the Moon.

Even during Apollo, astronauts were able to make some emergency repairs. In particular, on Apollo 17, Cernan and Schmitt, using a design devised and tested overnight in Houston, were able to make a replacement Rover fender using spare maps, clamps, and grey duct tape. The original fender had been damaged when Cernan inadvertently walked too close to it with a hammer dangling out of a suit pocket. The hammer caught under the fender and, because Cernan could not feel what was happening through the thick suit, the fender was torn off. At that point, Cernan attempted to re-attach the fender with tape and, not surprisingly, found that the dust - which tended to cover everything - prevented a good bond. The temporary repair lasted for about an hour's worth of driving; but a great deal of the ultimate success of the mission can be ascribed to the simple fact that Cernan and Schmitt had the opportunity to go back inside the LM, get out of the suits and gloves, and, with help from Houston, take time to fabricate a replacement fender in a relatively dust free environment.

At a lunar base, the ability to make repairs and modifications in a clean, shirt sleeve environment will be essential to productivity. the repair shop will need an adequate supply of tools - particularly a lathe - and a good supply of spare parts, including such things as wire made from lunar metals. The feasibility of repair and modification will be greatly aided if equipment designs are made as simple as possible and, as well, with repair and modification in mind.

Dust in everything

The problem of lunar dust is pervasive. The surface layers contain a high proportion of very fine particles which, because of their inherent dryness, tend to maintain a high electrostatic charge derived from their interaction with the solar wind. Almost any disturbance of the soil will loft a small cloud of particles which will rise much higher on the airless Moon than they would on Earth and which will tend to cling to anything they encounter. A walking astronaut lofts a particle cloud with every step and, because the particles fall so slowly under lunar gravity, a thick coat of dust will quickly accumulate on his legs as he walks thrugh the cloud. Before long, an astronaut will look, as CapCom Ed Gibson described Conrad and Bean, like someone who has just crawled out of a coal bin. Similarly, even with four good fenders, a Rover will quickly acquire at least a fine coat of dust.

The dust creates at least two potential hazards to lunar operations. First, dust-coated surfaces tend to absorb more sunlight, increasing thermal stress on equipment. The severity of the problem, particularly as it related to the Rover, had not been fully appreciated by the time of Apollo 15 and, on the last two missions, the commanders spent a few minutes at the beginning of each of the geology stops brushing dust off of thermally sensitive equipment. The second dust hazard is abrasion and mechanical clogging; and it was only on the Rover missions, particularly Apollo 17, that equipment was exposed long enough for problems to emerge. Toward the end of the third EVA, the replacement fender began to fail because of the more than twenty kilometers of steady sand-blasting; and a latch on the back gate was so hopelessly clogged that it stopped working. The astronauts' visors had become hopelessly scratched; frame count indicators on their cameras were unreadable because of the dust coating; and, in general, Schmitt thought that they were, at last, looking like a real geology expedition "all covered with dust."

Cernan said at point, with little exaggeration, that his dustbrush was his "most important tool"; and there is a general sense from this collective Apollo experience that dust may well prove to be the most serious impediment to productivity. In an effort to maximize the useful life of equipment intended for use outdoors, careful design attention should be paid to reducing vulnerability to abrasion, clogging, and thermal loading. Equipment should be designed so that it can be easily cleaned and, of course, roads and other prepared surface will be vital to the general reduction of the dust problem. Because lunar dust clings so easily to almost anything, careful attention will also have to be paid to keeping dust out of work and living areas.

The Fun of it All

In someways, it is a shame that most people who watched or heard any part of the Apollo missions experienced on Apollo 11. As probably befit the occasion, Armstrong and Aldrin did not crack a single joke for public consumption; nor did they sing or hum while they worked. However, working on the Moon can be, above all, an enormous amount of fun and I, for one, thoroughly enjoyed the later missions when, with the spotlights largely turned off, people like Pete Conrad, Dave Scott, Gene Cernan, and Jack Schmitt could relax a little bit and share their exhilaration.

Once you got the basics, moonwalking was fun, almost effortless; and, the scenery, was striking and, particularly at the mountainous sites, even spectacular. At Hadley Rille and, again, at the Valley of Taurus-Littrow, the crews of Apollo 15 and 17, respectively, did their work against the backdrop of mountains that rise abruptly from the valley floors to summits of up to four kilometers. Because of the soft contours of the dust-covered lunar landscape, the crews were often reminded of ski country and used ski terms a lot. At one point late in his mission, Jack Schmitt imagined himself skiing down off of the Sculptured Hills, making "whoosh" sounds as he hopped through the powder. And Gene Cernan looked out over the valley and the surrounding mountains and wished there were some air so that he could come roaring through in an airplane.

It was fun. It was spectacular. And it was little wonder that Pete Conrad was delighted to find that, even at 3.7 psi, he could whistle while he worked.

Acknowledgements and Sources

The material presented in this paper has been extracted almost entirely from the unpublished Lunar Surface Procedures volumes, Mission Reports, and Air-to-Ground Transcripts and audio tapes prepared by the National Aeronautics and Space Administration at the time of the missions The remaining material has been extracted from interviews with Harrison H. Schmitt.

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